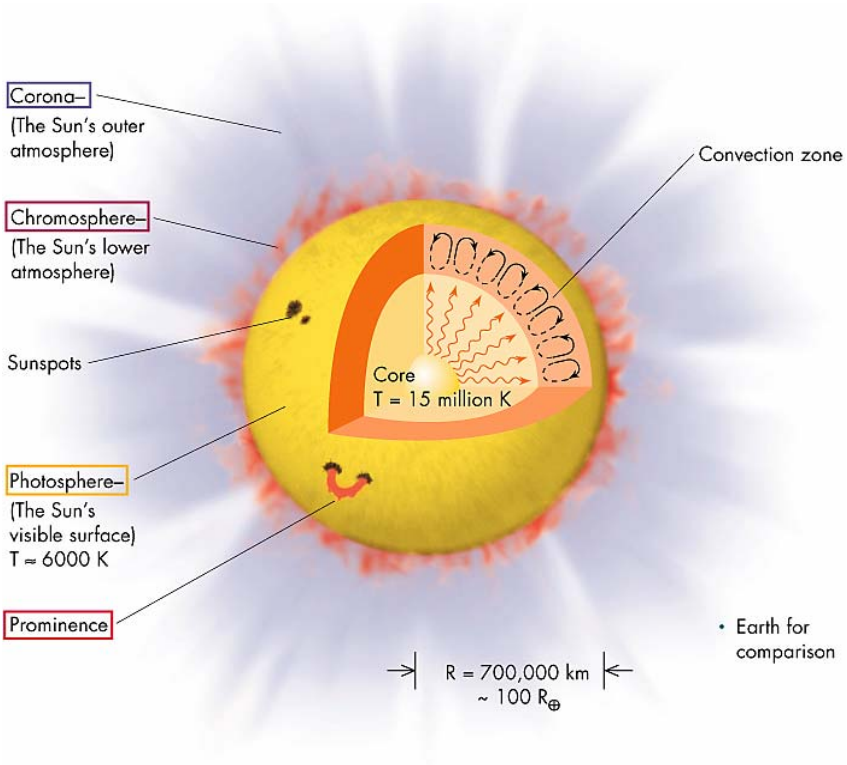
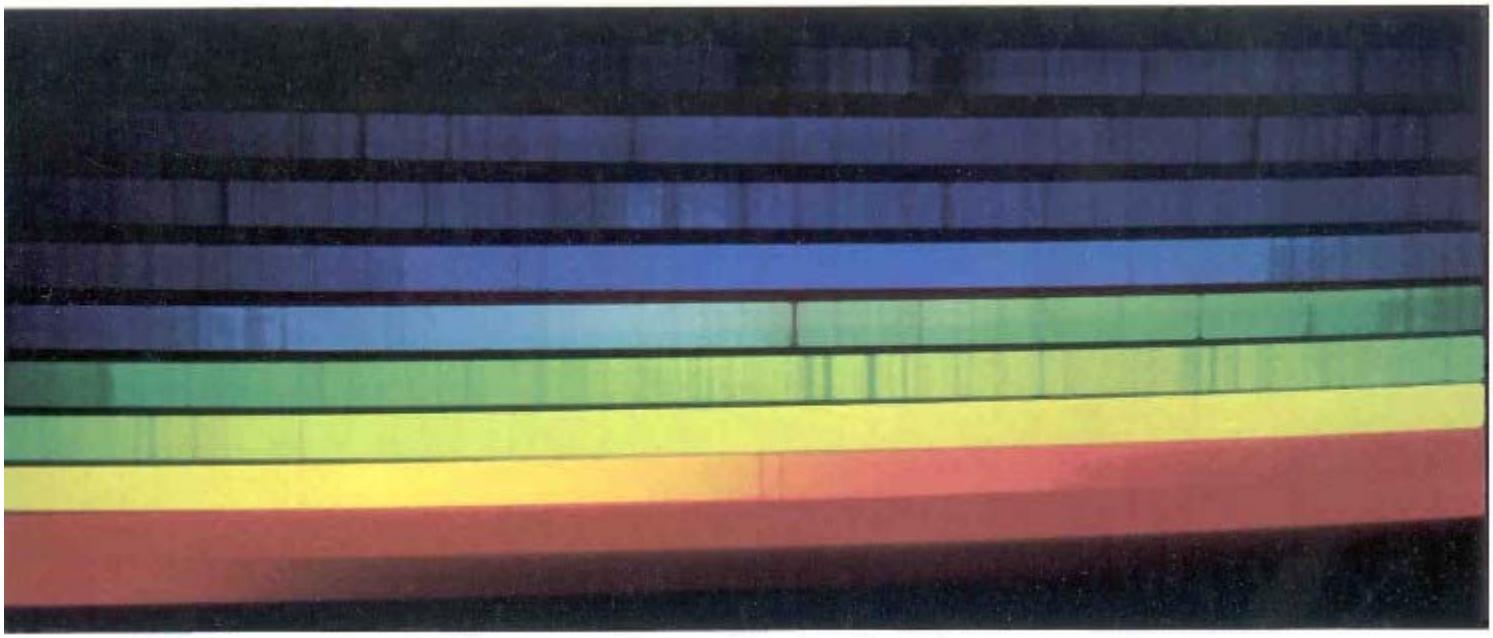
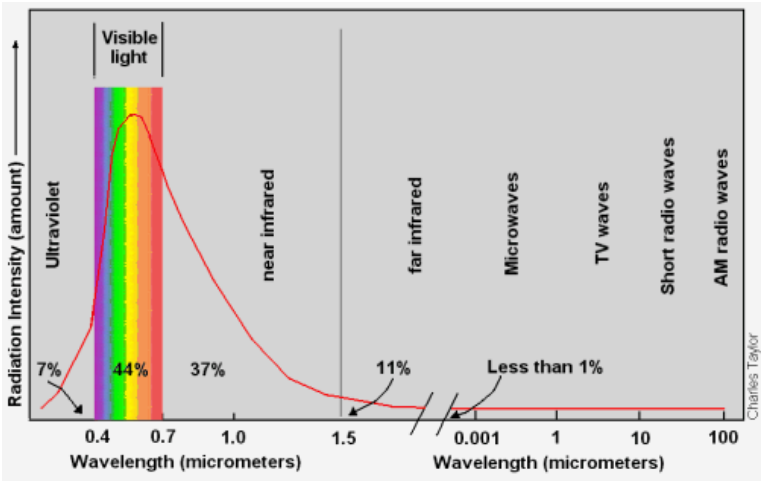
The Sun


Corona–
(The Sun's outer atmosphere)
Chromosphere–
(The Sun's lower atmosphere)
Sunspots
Photosphere–
(The Sun's visible surface)
T ≈ 6000 K
Prominence
Convection zone
Core
T = 15 million K
Earth for comparison
R = 700,000 km
~ 100 R⊕

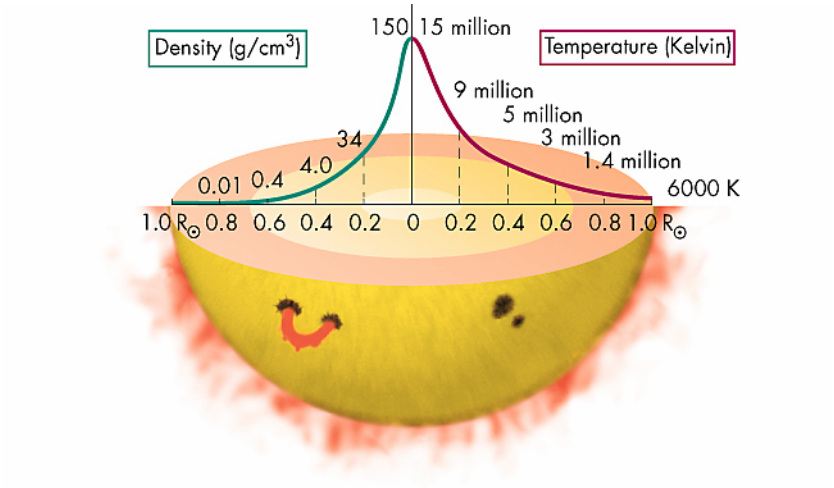


General Internal Structure

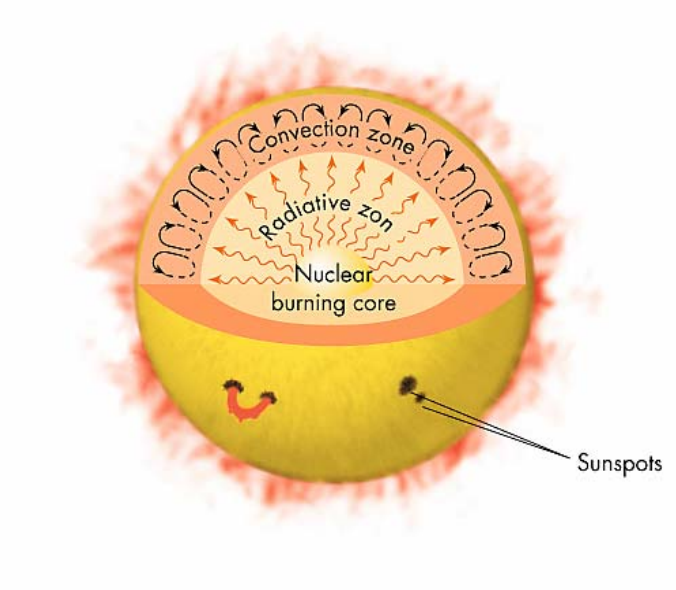
- 109 R_e, 333,000 M_e, 1 AU from Earth
- Surface Temperature: ~ 5800K (~ 10,000 ^{0}F). Deduced from it's color and Wein's Law
- Core Temperature: ~ 15 million K (~ 15 million ^{0}C, 27 million ^{0}F)
- 71% H, 27% He, 2% heavier elements
- Power: 4×10^{26} W
- Intensity at 1 AU: 1400 W/m^2
- Average power from the sun that falls on the earth's surface is 340 W/m^2 (worldwide)



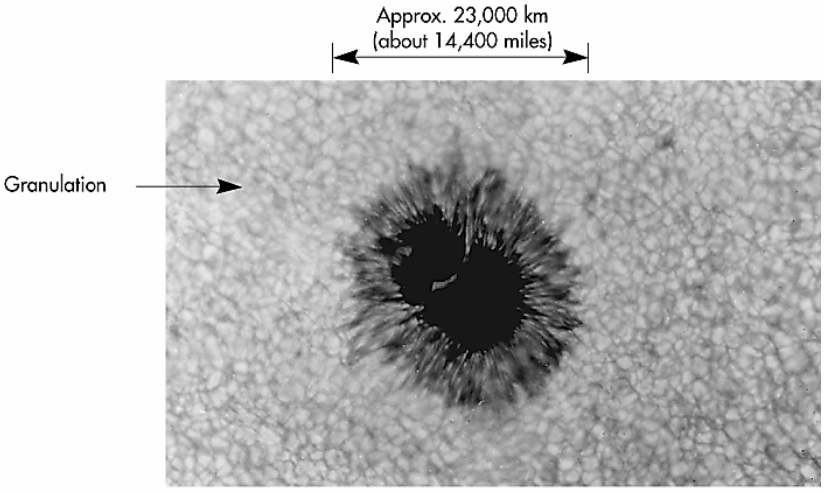
- Gaseous throughout in spite of densities as high as 100 times that of water!



- Light is absorbed in the denser inner layers of the sun preventing them from being transparent.
- Absorption of light is weaker in upper layers so light produced by the heat there escapes into space and forms the sunlight we see.
- The lower layers of the sun provide a layer of "insulation" that prevents it from using up its energy at a faster rate. The region of the sun where light begins from within begins to be strongly absorbed is known as the *photosphere*.



- Layers of the Sun: core, radiative zone, convection zone. photosphere
- The sun's heat originates in the thermonuclear core.
- Outside the core photons emitted by excited atoms travel through an area know as the *radiative zone*.
- Photons travel very short distances (less than an inch) before being absorbed by another atom in the radiative zone. This continual emission/absorption (scattering) process slows the speed at which photons travel from the core through the radiative zone to over 100,000 years (even though the photons travel at the speed of light between interactions).
- Thus today's sunlight originated from a reaction that occurred well before human civilizations began.
- The *convection zone* is a cooler layer outside the radiative zone. Because it is cooler it impedes energy transport from the center of the sun outward by photons. Instead convection currents transport the bulk of the energy from the core of the sun outward in this zone.



- Thermal "bubbles" rise at a rate of about 1 km/s in the convection zone.
- The *photosphere* is the visible surface of the sun.

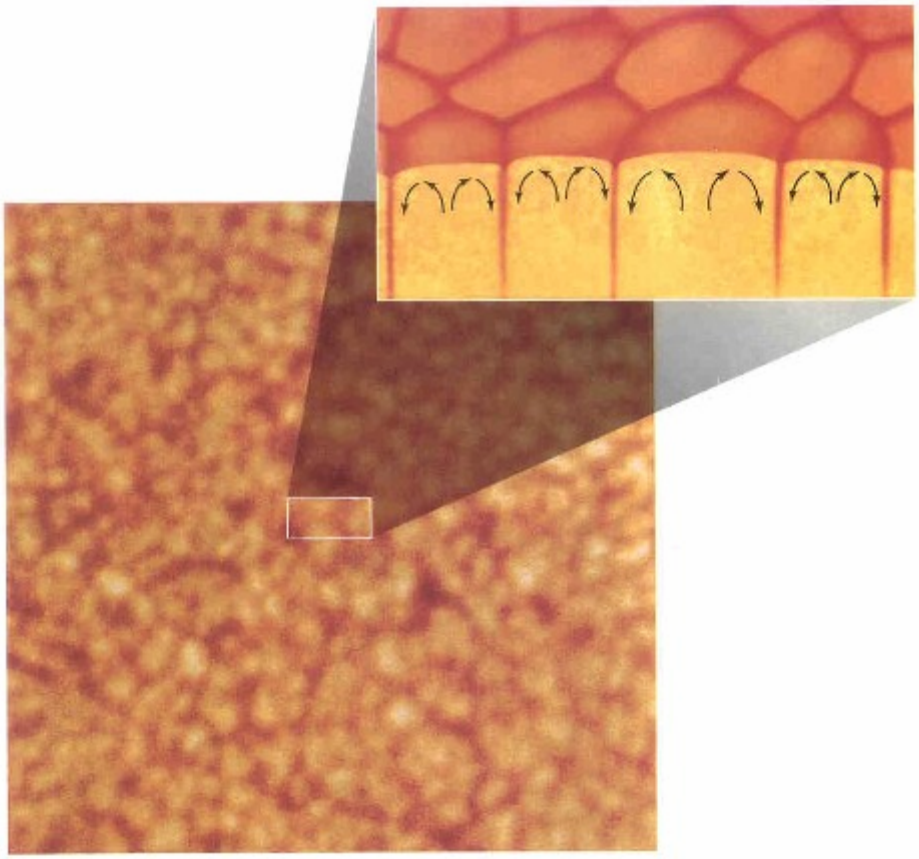


Figure 9-2
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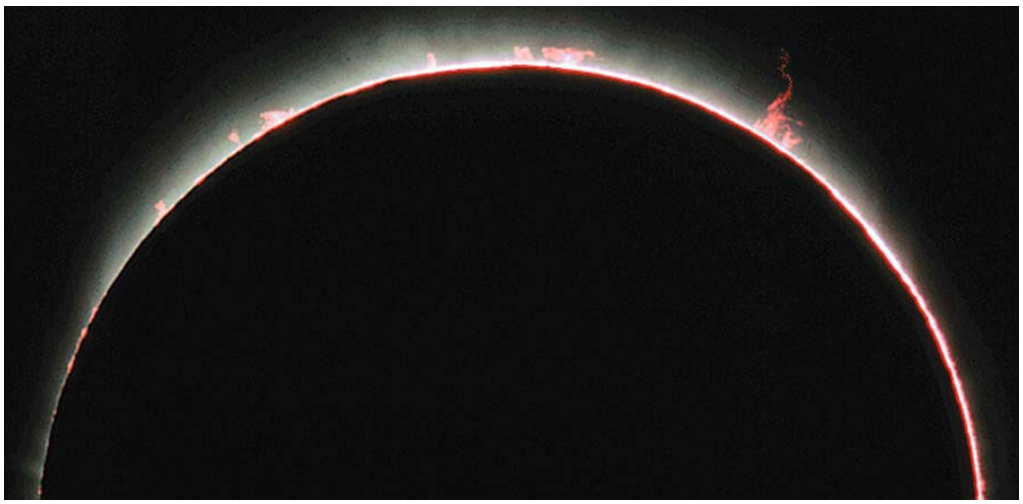
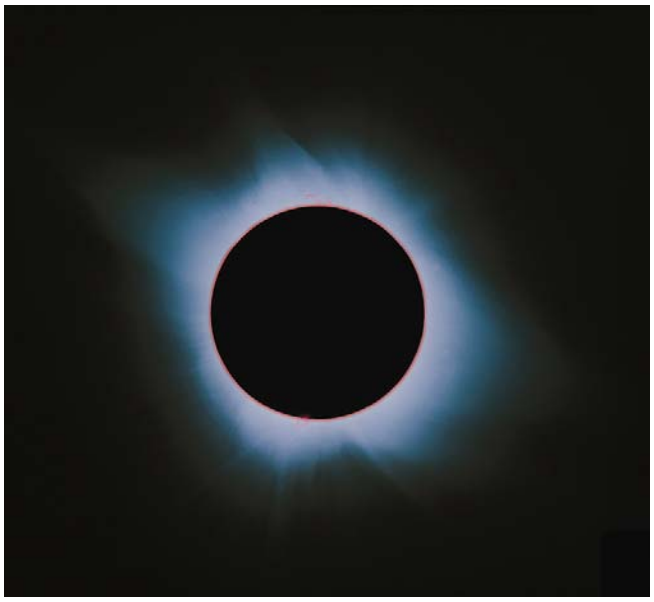
Atmosphere

- The solar atmosphere is region of cooler, low-density gasses that lie above the photosphere. This region eventually tapers into space.
- A temperature inversion exists everywhere in the sun's atmosphere.
- Two main layers: the *chromosphere* and the *corona*
- The chromosphere is the lower atmospheric layer immediately above the photosphere. The chromosphere consists of millions of thin columns of hot gas thousands of kilometers long known as *spicules*
- The red color of the chromosphere comes from the Hα emission line in hydrogen. This color is indicative of a temperature of around 4500 K.



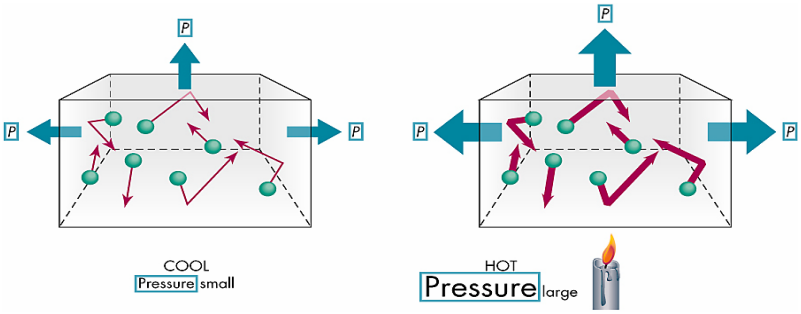
- About 2000 km above the photosphere the temperature of the sun's atmosphere reaches 50,000 K. At this point the temperature jumps rapidly to around 1 million K.
- The point where this rapid increase in temperature occurs marks the beginning of the *corona*.



- Corona usually transparent because of it's low density
- Corona extends into space several solar radii
- The Corona is nonuniform
- The Corona contains very little energy in spite of the fact that it is very hot
- The Corona is energized by the sun's intense magnetic field

How The Sun Maintains Hydrostatic Equilibrium

- Hydrostatic equilibrium: the balance between gravity and pressure
- Gravity pulls matter inward compressing it
- Pressure increases with increasing gravity.
- Pressure exerts a net outward force



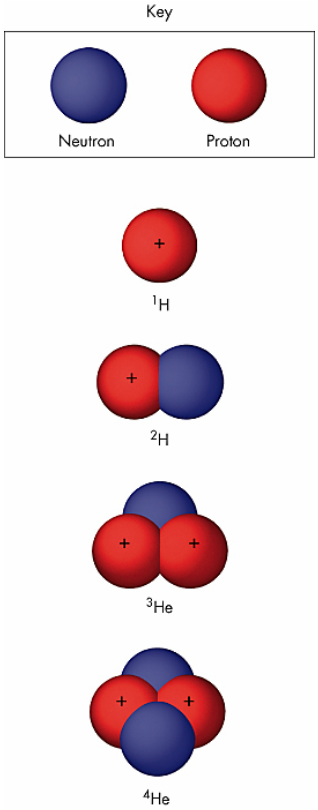
- The *ideal gas law,* $PV = nRT$, relates pressure, volume and temperature.
- For our sun T has been computed to be about 15 million K and *density* (mass per unit volume) has been computed to be about 150 grams/cm^3

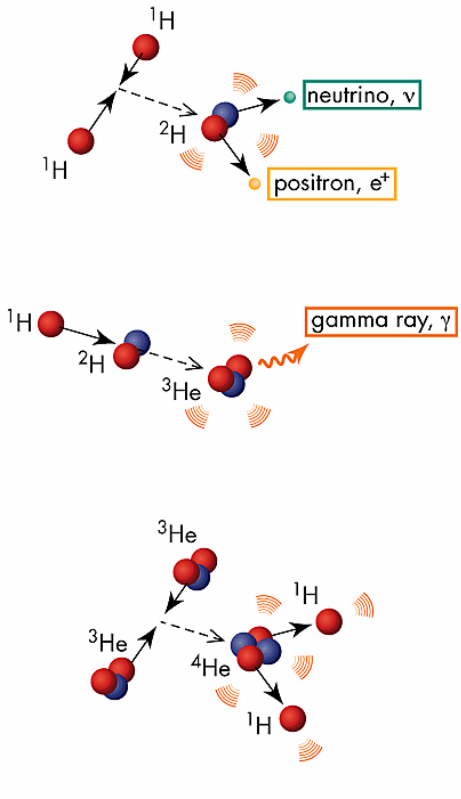
Nuclear Fusion

- $E = mc^2$
- $c = 3 \times 10^8 \, m/s$ the speed of light in free space
- 1 kg of dynamite liberates about 10^6 joules of energy when exploded. The conversion of 1 kg of matter to energy liberates:

$$(1kg) \times \left(3 \times 10^8 \, m/s\right)^2 = 9 \times 10^{16} \text{ joules!}$$

- 1 gram of mass when converted to pure energy liberates the equivalent of 20 kilotons of TNT (a relatively small nuclear weapon)
- Nuclear fusion occurs when two light nuclei are squeezed together with enough force to overcome the Coulomb repulsive force. The resulting nucleus has by a very small amount less mass than the two separate nuclei had. This lost mass is released as energy.
- Nuclear fusion requires very high temperatures and pressures (like those found in the core of a star).
- Nuclear fusion produces reaction by products such as neutrinos, gamma rays and positrons.





Hydrogen fusion in the sun occurs in three steps known as the proton-proton cycle:

1. ${}^1H + {}^1H \rightarrow {}^2H + e^+ + \nu +$ energy
2. ${}^1H + {}^2H \rightarrow {}^3He + \gamma +$ energy
3. ${}^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H +$ energy

- Notice that the first two steps must occur *twice* in order to produce the two ${}^3He$ nuclei required for the third step.
- 6 protons (${}^1H$), a.k.a. 6 hydrogen nuclei, are required to ultimately produce one ${}^4He$ nucleus and two ${}^1H$ nuclei. The net in this reaction is therefore 4 ${}^1H$ *in* and 1 ${}^4He$ *out* along with some fundamental particles, radiation and energy.
- If we ignore the small amounts of energy carried off by the reaction by products we can compute the energy liberated in the proton-proton cycle by simply comparing the mass of what goes into the reaction with what comes out

- To find the energy released we sum the initial masses and compare to the final mass. We then convert the missing mass (the difference in initial and final mass) to energy using $E = mc^2$.
- Recalling that steps one and two must occur twice to produce two ^4He nuclei for the last step:

$4 \times$ 1 hydrogen	$= 4 \times 1.673 \times 10^{-27}$ kg	$= 6.692 \times 10^{-27}$ kg
- 1 helium	$= 1 \times 6.645 \times 10^{-27}$ kg	$= 6.645 \times 10^{-27}$ kg
		$= 0.047 \times 10^{-27}$ kg

$E = \left(0.047 \times 10^{-27}\, kg\right) \times \left(3 \times 10^{8}\, m/s\right)^2 = 4.2 \times 10^{-12}$ joules

- This is a small amount of energy per fusion but the number of hydrogen atoms undergoing fusion in the sun at a time is vast.
- The total energy per second produced within the core of our sun is the equivalent of exploding 100 billion-megaton H bombs.